https://doi.org/10.52326/csd2025.27

CCS TECHNOLOGIES: ACCELERATORS OF SUSTAINABILITY

Silvia Elena Isachi[1], Georgiana Chițiga[2]

[1,2]*Centre of Financial and Monetary Research "Victor Slăvescu", Romanian Academy, Bucharest, Romania*

Abstract. In this paper, we aim to analyze the role of carbon capture and storage (CCS) technologies for reducing greenhouse gases in the context of global energy change and climate policies. High costs, the need for adequate infrastructure and the level of population acceptance are some of the challenges related to the implementation of these technologies. In addition, we will highlight the opportunities for innovation and the role of CCS as a "sustainability accelerator" in achieving the objectives of the Paris Agreement and the European Green Deal. CCS technologies have proven to be important tools in the transition to a sustainable future, complementing other emission reduction measures, such as renewable energies and energy efficiency. These technologies allow a considerable reduction of CO_2 emissions from hard-to-decarbonizes sectors, such as cement production, steelmaking or fossil fuel power generation. In conclusion, although CCS is not the only solution, its proper integration into the climate technology mix can have a particularly important effect on accelerating the transition to climate neutrality.

Keywords: *carbon capture and storage, climate neutrality, energy transition, emission reduction, sustainability.*

JEL code: *Q42, Q54*

Introduction

The climate crisis has become a reality that shapes economic, social and political decisions. Temperature changes, prolonged droughts, wildfires and extreme weather events are symptoms of a planetary system under stress. At the heart of this crisis is carbon dioxide (CO_2) – an inevitable result of an economy that has been built for over a century on burning fossil fuels. As scientific data confirms that global warming is accelerating, modern societies are faced with an important question: how can we develop economically without affecting the planet's climate stability?

The Paris Agreement (2015) sets the objective of limiting the increase in global temperature to "well below 2°C", with the ambition to keep it to 1.5°C. The European Union, through the European Green Deal, has committed to achieving climate neutrality by 2050, which requires a profound transformation of energy, industry and transport systems. In order to achieve these objectives, a significant reduction in CO_2 emissions from fossil fuel combustion and industrial processes is essential. Although renewable energy sources — solar, wind, hydro or geothermal — are central to this transition, they cannot currently completely eliminate emissions from "hard-to-abate" sectors, such as heavy industry (cement, steel, chemicals) or energy production from conventional sources. In these areas, emissions come not only from energy consumption, but also from the intrinsic chemical processes of production, which makes it impossible to achieve total decarbonisation by switching to green energy alone. This is where carbon captures and storage (CCS) technologies come in, offering a complementary and necessary solution to reduce emissions. CCS allows carbon dioxide to be captured directly from the source where it is emitted, transported through pipelines or other methods, and stored in deep geological formations so that it no longer enters the atmosphere. This way of working not only reduces industrial emissions, but can also lead to negative emissions when combined with energy from biological sources (BECCS) or direct carbon dioxide capture from air (DACCS).

Therefore, in this paper we aim to analyze the role of CCS technologies as "sustainability accelerators" in the context of the global and European energy transition. The main goal is to highlight

how these technologies can contribute to achieving climate neutrality objectives, complementing other emission reduction measures. So, we aim to:

- the operating principles of CCS technologies and their position within the decarbonization solution mix;
- assessing the potential impact of CCS in reducing greenhouse gas emissions, by analyzing some application areas and international case studies;
- identifying the main economic, technological and social challenges associated with CCS implementation;
- proposing directions for the development and integration of CCS into future climate strategies, especially within the European Union.

By addressing these objectives, the paper aims to highlight the importance of CCS not only as an emissions reduction technology, but as a strategic tool in accelerating the transition to a sustainable and competitive economy. In a world where time for action is getting shorter, CCS can become a key element of a diversified portfolio of climate solutions, capable of supporting the achievement of ambitious neutrality targets and contributing to redefining the relationship between industry, the environment and economic development.

Carbon capture and storage technologies in the context of the energy transition

Carbon Capture and Storage (CCS) technologies are a category of technological solutions designed to reduce industrial CO_2 emissions by preventing their release into the atmosphere. According to the Global CCS Institute report (2024), CCS technologies operate on the basis of three fundamental steps:

a). Capture of carbon dioxide at the emission source. CO_2 capture can be achieved through several technologies:

- *post-combustion,* where CO_2 is separated from the flue gases after the combustion of fuels;
- *pre-combustion,* where carbon is removed before combustion, in the form of synthesis gas;
- *oxy-combustion,* which involves burning the fuel in pure oxygen, resulting in a concentrated mixture of CO_2 and water vapour that is easily separated.

b). Transport of the captured gas, usually by pipeline or sea transport. After capture, the CO_2 is compressed and transported to a storage site.

c). Storage in deep geological formations, such as depleted oil reservoirs, salt layers or natural gas fields. The geological formations used must have high capacity, structural stability and tightness, to prevent leakage. Geological studies show that Europe has significant storage potential, especially in the North Sea basin.

The technological process of carbon dioxide capture and storage consists of a sequence of interdependent stages that transform industrial emissions into a manageable and controlled flow. (Figure 1).



Figure 1. Simplified diagram of the CCS chain (capture, transport, underground storage)
Source: data processing by authors based on report from the International Energy Agency (IEA), 2020.

Figure 1 illustrates the overall flow of the CCS process, starting with the capture of CO_2 from the industrial source, followed by its transport through dedicated pipelines and ending with geological storage in deep, sealed formations. The representation highlights the integrated nature of the CCS chain, where each stage is essential to ensure the efficiency and safety of the entire system.

The energy transition involves the simultaneous use of several technological solutions aimed at reducing greenhouse gas emissions. Each of these solutions has advantages, limitations and specific areas of application. To highlight the position of CCS technologies in relation to other decarbonisation options, a comparative table is presented below (table 1).

Table 1. Comparative role of the main decarbonisation solutions

Technological solution	Main field of application	Advantages	Limitations
Renewable energy	Electricity Generation	Clean sources, decreasing costs	Variability, dependence on weather conditions
Energy efficiency	All Sectors	Direct consumption reduction	Limited potential in heavy industries
Green hydrogen	Industry, Heavy Transport	No direct emissions	High production costs, lack of infrastructure
CCS / CCUS	Heavy Industry, Energy, Blue Hydrogen	Significant emission reduction, high scalability	High costs, geological and infrastructural requirements

Source: data processing by authors based on report from the International Energy Agency (IEA) 2021.

Table 1 summarizes the complementary role of CCS technologies in the context of the decarbonisation solution mix. While renewable and energy efficiency aim to reduce emissions at source, CCS addresses residual emissions, specific to heavy industry and conventional power generation. Through its ability to capture and store CO_2 in large volumes, CCS complements renewable solutions, helping to maintain the balance between climate objectives and the economic needs of the energy transition. According to the International Energy Agency (IEA), achieving climate neutrality by 2050 requires the annual capture of over 4–5 gig tonnes of CO_2 globally, of which around 15–20% comes from heavy industry.

In the current context of accelerated decarbonisation, CCS is not only an emission reduction technology, but also a strategic tool for balancing the energy transition. On the one hand, it allows the continued use of fossil fuels in a controlled manner compatible with climate objectives; on the other hand, it creates new industrial value chains – from storage services to the conversion of CO_2 into raw materials for industry (CCU). At the same time, CCS supports the development of blue hydrogen, produced from natural gas with CO_2 capture, which can be used as a transitional energy source until the full maturity of green hydrogen. Thus, CCS becomes a technological bridge between the present and the future energy system based entirely on renewable sources.

The large-scale implementation of CCS technologies is conditioned by a series of technical, economic, environmental and social factors. To understand the strategic position of CCS in the energy transition, it is useful to compare the benefits it offers and the challenges associated with its implementation (table 2).

Table 2. Synthesis of CCS advantages and challenges in energy transition

Aspect	Main advantages	Major challenges
Technological	Mature technology, industrially applicable	High capture costs (50–100 €/t CO_2)
Economic	Can maintain the competitiveness of heavy industries	Requires large investments in infrastructure
Environmental	Reduces emissions in hard-to-decarbonise sectors	Requires long-term geological monitoring
Political / Social	Supported by European climate policies	Variable public acceptability

Source: data processing by authors based on reports from the International Energy Agency (IEA), 2020 and the European Commission, 2023.

Table 2 highlights the dual nature of CCS technologies: on the one hand, they offer a solid technological solution for the decarbonisation of industrial sectors that are difficult to electrify; on the other hand, their large-scale implementation requires significant costs, complex infrastructure and constant political support. In addition, the success of CCS depends on social acceptance and the creation of a stable legislative framework that encourages investment and guarantees the safety of storage processes. Thus, CCS is not just an emissions reduction technology, but an element of balance between climate objectives and the need to maintain European economic competitiveness.

The contribution of CCS to reducing greenhouse gas emissions

Carbon capture and storage (CCS) technologies represent one of the most promising options for rapidly and sustainably reducing greenhouse gas (GHG) emissions, particularly in industrial sectors where decarbonisation alternatives are limited. Unlike energy efficiency measures or the transition to renewable, CCS does not eliminate the need for fossil fuels, but rather provides a technological pathway for managing residual emissions by capturing CO_2 before it is emitted into the atmosphere and storing it in stable geological formations.

According to the International Energy Agency (2024), CCS will contribute about 15% to the total reduction of global emissions by 2050, remaining essential for hard-to-decarbonise sectors such as cement, steel and refining. This potential is due to the versatility of the technology, which can be used in many different areas — from electricity and cement production, to refineries, steelworks, and the chemical industry and even in transport, by creating synthetic fuels or low-emission hydrogen (“blue hydrogen”).

The first commercial geological CO_2 storage project, operational since 1996, injecting over 1 million tonnes of CO_2 annually into the Utsira underground reservoir is the *Sleipner* project in Norway. The *Boundary Dam* project in Canada has also demonstrated the economic viability of capturing CO_2 from coal-fired power plants, while recent initiatives such as *Northern Lights* (Norway) and *Porthos* (Netherlands) aim to create regional transport and storage infrastructures capable of serving multiple industries simultaneously.

At the European level, CCS is strategically integrated into climate policy packages, being recognized by documents such as the *EU Green Deal (2019), Fit for 55* and the *Industrial Carbon Management Strategy (2023)*. These initiatives aim not only to reduce emissions, but also to stimulate a circular carbon economy, in which captured CO_2 can be reused in industrial processes (CCU – Carbon Capture and Utilization), thus contributing to the development of new value chains and green industries.

In its Towards an ambitious *Industrial Carbon Management for the EU (COM/2024/62)*, the *European Commission* (2024) highlights that carbon capture and storage (CCS) technologies are an essential pillar of the energy transition, being integrated into plans for the development of cross-border CO_2 transport infrastructure and the creation of industrial hubs dedicated to reducing emissions.

The potential impact of CCS on climate neutrality is significant: according to the IEA’s Net Zero 2050 scenario, over 1.2 billion tonnes of CO_2 could be captured annually by 2030, and this capacity would need to exceed 6 billion tonnes annually by 2050 to stay on the 1.5°C trajectory. Thus, CCS becomes not just a transitional technology, but a structural element of the future energy system, capable of balancing sectors that are difficult to electrify and ensuring the stability of energy networks based on renewable sources.

To better understand the role of CCS technologies in reducing greenhouse gas emissions, Table 3 summarizes several projects implemented in the main regions of the world, highlighting the accelerated expansion of storage capacity in Europe and North America. These initiatives demonstrate the applicability of CCS in various industrial sectors and its relevance in supporting global climate goals. Data from 2024 confirm the upward trend in investments and projects in various stages of development. Cumulatively, these projects contribute to the reduction of over 10 million tons of CO_2 annually, demonstrating the technological and economic viability of CCS.

According to the Global CCS Institute (2024) report, 2024 marks the largest global expansion of CCS projects to date, with over 250 initiatives in various stages of development. The growth is mainly driven by ambitious climate policies in the US, EU and Asia-Pacific, as well as the expansion of cross-border transport and storage infrastructure. This development confirms the maturation of CCS technologies as a key tool in achieving global climate neutrality by 2050.

Table 3. International examples of CCS projects and their annual CO_2 capture capacity

No.	Project / Country	Application sector	Capture capacity (Mt CO_2/year)	Release year	Observations
1	Sleipner (Norway)	Energy – natural gas	1,0	1996	First commercial offshore geological storage project
2	Boundary Dam (Canada)	Energy – coal	1,0	2014	Successful demonstration of post-combustion capture
3	Petra Nova (USA)	Energy – coal	1,4	2017	CO_2 capture for enhanced oil recovery
4	Gorgon (Australia)	Natural gas	4,0	2019	Largest onshore geological storage project
5	Northern Lights (Norway)	Multi-industrial (regional hub)	1,5 (extensible)	2024	Shared infrastructure for captured CO_2 in the EU

Source: data processing by authors based on report from the Global CCS Institute, 2024.

To contextualize the impact of CCS within the global decarbonisation efforts, we present the estimated share of this technology in the solution mix that will contribute to total emission reductions by 2050, according to the Net Zero by 2050 scenario developed by the International Energy Agency (IEA). Renewable energy and energy efficiency dominate the solution mix, but CCS remains essential for hard-to-electrify sectors. With a contribution of around 15% to total reductions, CCS plays a critical role in capturing residual emissions from industry and energy, as well as in the development of negative emissions technologies such as BECCS (bio energy with carbon capture) and DACCS (direct air capture). This share confirms the status of CCS as a structural element of global decarbonisation, indispensable for achieving climate neutrality by 2050 (Figure 2).

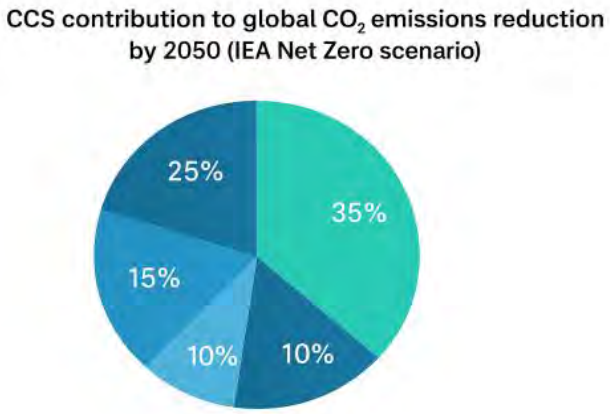


Figure 2. CCS contribution to global CO_2 emissions reduction by 2050 (IEA NET ZERO scenario)

Source: data processing by authors based on report from the International Energy Agency (IEA), 2021

The graph shows the complementary role of CCS (15%) in the global climate solution mix, alongside renewable energy (35%), energy efficiency (25%) and low-emission hydrogen (10%), according to the IEA Net Zero 2050 scenario.

Challenges and opportunities

Carbon capture, utilization and storage (CCS) technologies represent one of the most promising solutions for reducing greenhouse gas (GHG) emissions, but also one of the most complex and controversial components of the energy transition. Although they can significantly contribute to achieving global climate goals, the implementation of CCS faces a diverse set of economic, technological, infrastructure and social acceptability challenges, along with numerous opportunities related to innovation, international cooperation and the creation of new industrial value chains.

Major challenges

a) Economic aspects: High costs remain one of the main barriers to the large-scale implementation of CCS. Capturing a tonne of CO_2 can range from USD 50 to USD 120, depending

on the source and technology, and transport and storage costs add an additional burden. In the absence of clear support mechanisms – such as a carbon price, emission allowances or tax incentives – private investment is often discouraged. Also, the long payback period limits the attractiveness of CCS projects compared to other faster decarbonisation solutions such as energy efficiency or renewable energy.

b) Technological challenges: Even though the principles of CCS are well understood, technological performance is still variable. Capturing CO_2 from low-concentration sources (e.g. from waste gases or lean combustion processes) requires advanced technologies and high energy consumption. In addition, the lack of a mature infrastructure for the transport and storage of CO_2, including pipelines and verified geological sites, limits its applicability on an industrial scale. Long-term monitoring of underground storage is essential for safety, but involves additional costs and strict regulatory requirements.

c) Social acceptability and regulatory issues: Another obstacle is public perception. In some regions, CCS projects have been challenged due to concerns about CO_2 leakage, seismic risks or the "postponement effect" on the transition to renewable. In the absence of a coherent legislative framework and information campaigns, social acceptance remains limited. At the same time, the lack of coordination between national and regional climate policies can lead to investment uncertainty and implementation delays**.**

Emerging opportunities

a) Technological innovation and competitiveness: progress in absorbent materials, cryogenic technologies, membrane processes and biochemical solutions promises to significantly reduce the costs of CCS. In addition, the emergence of direct air carbon capture (DACCS) and bio energy with carbon capture and storage (BECCS) technologies extend the potential of CCS beyond simple industrial processes, offering the possibility of achieving negative emissions. Companies investing in such technologies become pioneers in an emerging sector, with the potential to export know-how and specialized services.

b) Development of infrastructure and regional cooperation: CCS offers the opportunity to create integrated industrial hubs, where several economic units can use common infrastructure for capture, transport and storage.

c) Public policies and strategic integration: in the context of the European Green Deal and the Net Zero Industry Act, CCS is recognized as a strategic technology for climate neutrality. Member States can benefit from innovation funds, carbon credits and public-private partnerships to accelerate implementation. In addition, the integration of CCS with renewable sources and the circular economy creates new opportunities for synergy between sustainability and industrial competitiveness.

General perspective

Overall, CCS is at a turning point. While the economic and infrastructure challenges are considerable, the global pressure to reduce emissions rapidly and the progressive maturity of the technology are transforming CCS from a theoretical option into a strategic tool for achieving climate neutrality. With investment in research and transparent public communication, CCS can become not just a transitional solution, but an accelerator of sustainability, contributing to the balance between industrial development and environmental protection.

To summarize the complexity of the topic, Table 4 presents the main challenges facing CCS technologies, along with the opportunities they can generate in the context of the global energy transition. The table provides an overview of the economic, technological, social and political dimensions involved.

Although CCS implementation is associated with considerable economic and technical challenges, the potential for innovation, European political support and opportunities for creating transnational infrastructure can transform these difficulties into strategic advantages, in particular the development of regional hubs and the introduction of carbon pricing policies can make CCS a competitive and sustainable solution in the next decade.

Table 4. The main challenges and opportunities of CCS technologies

Category	Main challenges	Emerging opportunities	Potential impact
Economic	High capture and storage costs; lack of a sufficiently incentivizing carbon price	Access to innovation funds, public-private partnerships, emerging carbon markets	Boosting green investment and industrial competitiveness
Technological	Low energy efficiency, lack of CO_2 transport infrastructure, technical storage risks	Development of DACCS and BECCS technologies, optimization of capture processes, increasing reliability	Reducing costs and extending CCS applicability to new sectors
Social	Negative perception of safety and environmental effects; lack of public information	Creation of green jobs, involvement of local communities, education and transparency	Increasing social acceptability and strengthening public trust
Political and legislative	Lack of a unified regulatory framework, slow approval processes	Integration of CCS into European climate strategies (Green Deal, Net Zero Industry Act)	Coherence in climate policies and attracting transnational investment

Source: data processing by authors based on reports from the International Energy Agency (IEA), 2020; *Global CCS Institute, 2023 and European Commission, 2023.*

Conclusions

In the context of accelerating climate change and the need to achieve climate neutrality by 2050, carbon capture, utilisation and storage (CCS/CCUS) technologies represent one of the most promising complementary solutions for reducing greenhouse gas emissions. This paper has highlighted the fact that, although the global energy transition is dominated by the expansion of renewable sources and increasing energy efficiency, CCS remains a strategic link in the technology mix for decarbonisation, especially for industrial sectors that are difficult to electrify (cement, steel, refining, and petrochemicals).

CCS is not only a transitional technology, but an essential component of a net-zero emissions economy, as it allows the capture of residual emissions and paves the way for the development of negative emissions solutions, such as BECCS and DACCS. This amplifies the role of CCS beyond emission reduction, transforming it into an active tool for restoring the global climate balance.

The results of the analyses and the examples presented confirm that CCS technologies can act as sustainability accelerators by:

- Integration into existing industrial value chains, reducing the carbon footprint without compromising economic competitiveness;
- Creation of shared infrastructures (transport networks, storage hubs), which stimulate regional cooperation and technological innovation;
- Synergy with renewable sources and the circular economy, by transforming captured CO_2 into usable resources (methanol, synthetic fuels, construction materials);
- Development of human and technological capital, by attracting investments in research, education and professional training in green fields.

Thus, CCS contributes not only to reducing emissions, but also to creating a sustainable, circular and resilient economy, capable of combining environmental performance with economic development.

Despite its high potential, CCS still faces significant challenges: high costs, lack of transport and storage infrastructure, insufficiently harmonised regulations and sometimes negative public perception. To overcome these barriers, the following directions are essential:

- Strengthening financial support, through coherent carbon pricing policies and support mechanisms dedicated to CCS projects;
- International and regional cooperation, in particular through the development of integrated industrial hubs and cross-border CO_2 transport networks;

- Investment in research and innovation, to reduce costs and improve the efficiency of capture and storage processes;

- Communication and public education, to increase the level of trust and social acceptability of these technologies.

In conclusion, CCS technologies should not be seen as an alternative to renewable energy, but rather as a complementary technology, providing emission reductions where other solutions cannot effectively act — a bridge between the fossil fuel-dominated present and a future based on sustainability, innovation and climate responsibility. At the same time, the success of CCS depends on sustained public and private investment, clear regulations on storage responsibility and increasing public confidence in the safety of these processes.

References

1. BUI, M., ADJIMAN, C. S., BARDOW, A., ANTHONY, E. J., BOSTON, A., BROWN, S., FENNELL, P. S., FUSS, S., GALINDO, A., HACKETT, L. A., HALLETT, J. P., HERZOG, H. J., JACKSON, G., KEMPER, J., KREVOR, S., MAITLAND, G. C., MATUSZEWSKI, M., METCALFE, I. S., PETIT, C., MAC DOWELL, N. (2018). *Carbon capture and storage (CCS): The way forward.* Energy & Environmental Science, 11(5), 1062–1176. https://doi.org/10.1039/C7EE02342A
2. GIBBINS, J., & CHALMERS, H. (2021). *Carbon capture and storage: Realizing the potential of CO_2 capture technologies.* Nature Energy, 6, 1094–1105.
3. HASZELDINE, R. S., FLUDE, S., JOHNSON, G., & SCOTT, V. (2018). *Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments.* Philosophical Transactions of the Royal Society A, 376(2119). https://doi.org/10.1098/rsta.2016.0443
4. KOORNNEEF, J., VAN HARMELEN, T., VAN HORSSEN, A., & RAMIREZ, A. (2020). *Life cycle assessment of carbon capture and storage: A review.* International Journal of Greenhouse Gas Control, 94, 102906.
5. ZAKKOUR, P., & COOK, G. (2022). *CCUS: From emissions reduction to climate restoration.* Journal of Cleaner Production, 350, 131544.
6. BP. (2023). *Statistical Review of World Energy 2023.* BP. https://www.bp.com/statisticalreview
7. European Commission. (2020). *A European Green Deal: Striving to be the first climate-neutral continent.* European Commission, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
8. European Commission. (2022). *REPowerEU Plan – Accelerating the Clean Energy Transition* [COM(2022)230 final]. European Commission
9. European Commission. (2023a). *Industrial Carbon Management Strategy.* European Commission. https://energy.ec.europa.eu
10. European Commission, (2023b). *Net-Zero Industry Act* [COM(2023)161 final]
11. European Commission. (2024). *Towards an ambitious Industrial Carbon Management for the EU* (COM/2024/62 final). Brussels: European Commission.
12. European Environment Agency. (2024). *Trends and projections in Europe 2024.* European Environment Agency. https://www.eea.europa.eu
13. Global CCS Institute. (2024). *Global Status of CCS 2024 Report.* Melbourne: Global CCS Institute.
14. Intergovernmental Panel on Climate Change. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.
15. International Energy Agency. (2020). *CCUS in Clean Energy Transitions.* International Energy Agency. https://www.iea.org/reports/ccus-in-clean-energy-transitions
16. International Energy Agency. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector.* International Energy Agency. https://www.iea.org/reports/net-zero-by-2050
17. International Energy Agency. (2024). *Net Zero by 2050: 2024 Update.* Paris: IEA.
18. United Nations Environment Programme. (2023). *Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions.* United Nations Environment Programme.
19. World Bank. (2024). *State and Trends of Carbon Pricing 2024.* World Bank Group. https://www.worldbank.org/en/topic/climatechange/publication/state-and-trends-of-carbon-pricing